

# LAT Light Curve Analysis: Aperture Photometry and Likelihood-based Light Curves

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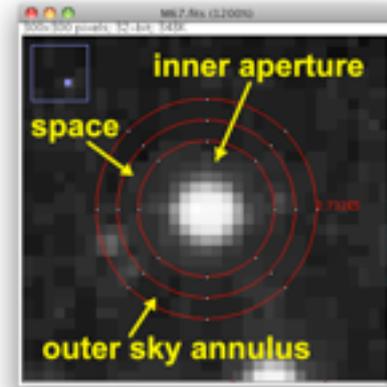
# Presentation Outline

- Photometry
  - Two methods (aperture photometry & likelihood)
  - LAT specific considerations
- Recipe for LAT aperture photometry
  - Light curve of 3C 454.3
  - Error bars for low count rates
- Recipe for LAT likelihood photometry
  - Example likelihood script (`like_lc.pl`)
  - Light curve of binary LS I +61 303 - comparison of likelihood and aperture photometry.

# LAT Photometry

- LAT light curves can be obtained in two basic ways:
  - Likelihood analysis
  - Aperture photometry
- Likelihood analysis has the potential for greater sensitivity and absolute flux measurements.
- Aperture photometry is easier, faster, and has the benefit of model independence.

# Aperture Photometry



- The simplest form of photometry is aperture photometry.
  - You just measure the flux collected inside a particular region of the sky.
- This is originally done with optical telescopes by using a physical aperture (e.g. a hole in a piece of metal).
- Now, with imaging instruments, it is possible to use a software defined aperture.

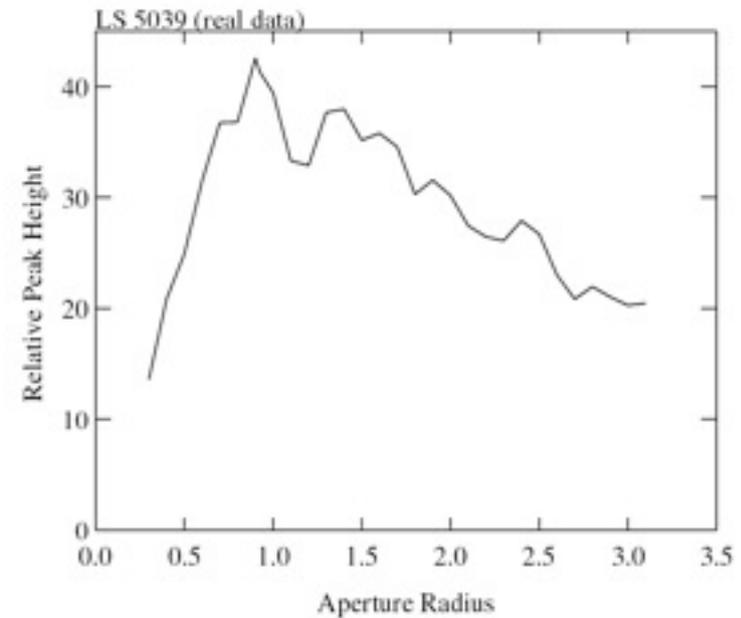
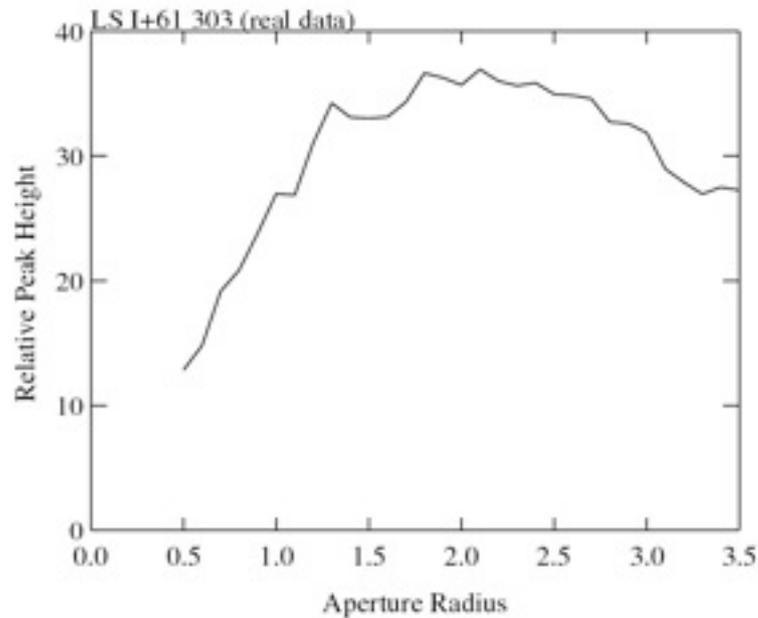
# Things to be Aware of with Aperture Photometry

- The aperture contains photons from not just the source you're interested in.
  - It also contains photons from nearby sources and the background. The background is particularly strong in the Galactic plane.
- The aperture can be made smaller to reduce the background. But this also reduces the number of photons from the source.
- The aperture can be made larger to increase the photons from the source. But this increases the background.

# LAT Aperture Optimization

- In optical/X-ray, aperture photometry relatively straightforward. e.g. point spread function not energy dependent as it is with the LAT.
- Want to choose aperture to maximize signal to noise ratio:
  - $S/N = S/(S + B)^{1/2}$  (S = source photons, B = background)
- LAT aperture photometry complicated by:
  - PSF energy dependence
  - Background from other sources and Galactic plane is complex and energy dependent.
- Optimum aperture size and energy range to maximize S/N varies from source to source...

# LAT S/N aperture dependence



For two different sources the optimum signal-to-noise ratio is obtained for different radii.

But, for many sources 1 degree radius seems to work fairly well!

# Tools Used for Aperture Photometry

- Data server
- fkeypar/pget
- gtselect
- gtmktime
- gtbin
- gtexposure
- fv; or fdump + external data manipulation scripts

# Steps

- It is recommended to use a script to chain together the tools.
  - (gtselect - combine together all photon files)
  - (fkeypar – determine file start and stop times)
  - gtselect – filter data based on time, zenith limit, energy, position, and event class
  - gtmktime – create good time intervals
  - gtbin – make quasi-light curve (counts rather than rate)
  - (gtbary - barycenter correction)
  - fv/fdump/other tools – convert counts to rates, calculate errors, convert MET -> MJD

# Get Photon and Spacecraft File Start/Stop Times

Before doing this, if you have multiple photon files, you may want to combine them together using `gtselect`.

If you are not going to do barycenter correction, then you generally don't need to bother determining the start and stop times! (Use "0" as start and stop time.)

```
$ fkeypar "L090923112502E0D2F37E71_PH00.fits[1]" TSTART  
(photon start time = 266976000.)
```

```
$ fkeypar "L090923112502E0D2F37E71_PH00.fits[1]" TSTOP  
(photon stop time = 275369897.)
```

```
$ fkeypar "L090923112502E0D2F37E71_SC00.fits[1]" TSTART  
(spacecraft start time = 266976000.)
```

```
$ fkeypar "L090923112502E0D2F37E71_SC00.fits[1]" TSTOP  
(spacecraft stop time = 275369896.360675)
```

The values obtained with "fkeypar" are accessible using "pget"

# Filter the Photon File

```
$ gtselect zmax=105 emin=100 emax=200000 infile="L090923112502E0D2F37E71_PH00.fits"  
outfile=temp2_1DAY_3C454.3 ra=343.490616 dec=16.148211 rad=1 tmin=266976000.  
tmax=275369897. evclsmin=3 evclsmax=10
```

Parameters specify:

- Energy range (100 to 200,000 MeV)
- Source coordinates
- 1 degree radius aperture
- start and stop times previously determined  
(N.B. If you're going to barycenter then the min and max times should instead be slightly greater/less than the times in the spacecraft file.)
- evclsmin = 3 for DIFFUSE class (for simulated data use 0)

Writes to file: temp2\_1DAY\_3C454.3

# Calculate GTIs (Good Time Intervals)

```
$ gtmktime scfile="L090923112502E0D2F37E71_SC00.fits" filter="(DATA_QUAL==1) &&  
(LAT_CONFIG==1) && (angsep(RA_ZENITH,DEC_ZENITH,343.490616,16.148211)+1<105)  
&& (angsep(343.490616,16.148211,RA_SCZ,DEC_SCZ)<180)" roicut=n  
evfile="temp2_1DAY_3C454.3" outfile="temp3_1DAY_3C454.3.fits"
```

Parameters specify:

- Good data quality
- photons less than 105 degrees from zenith (+ 1 is because using a 1 degree aperture)
- photon locations less than 180 degrees from center of field of view (180 degrees will include all data! change the value if you only want the center of the FOV)
- input file is output from gtselect

Writes to file: temp3\_1DAY\_3C454.3.fits

# Extract a Light Curve

```
$ gtbin algorithm=LC evfile=temp3_1DAY_3C454.3.fits outfile=lc_1DAY_3C454.3.fits  
scfile=L090923112502E0D2F37E71_SC00.fits tbinalg=LIN tstart=266976000.  
tstop=275369897. dtime=86400
```

Parameters specify:

- Make a light curve (LC)
- Input file is output file from gtselect
- Output file is lc\_1DAY\_3C454.3.fits
- Spacecraft file
- Linear time bins
- Start and stop times again
- dtime = 86400: 1 day bins

Writes to file: lc\_1DAY\_3C454.3.fits

# Calculate Exposures of Time Bins (the slowest step)

```
$ gtexposure infile="lc_1DAY_3C454.3.fits" scfile="L090923112502E0D2F37E71_SC00.fits"  
irfs=P6_V3_DIFFUSE srcmdl="none" specin=-2.1
```

Parameters specify:

- Spacecraft file
- Instrument response functions (“irfs”). If, for example, SOURCE class rather than DIFFUSE was used in gtselect then use `irfs="P6_V3_SOURCE"`
- `srcmdl` – enables a more complex model than the default simple power law to be used in the exposure calculation.
- `specin` – photon spectral index for power-law spectrum. Note that the minus sign must be used.

An EXPOSURE column is added to the input file: `lc_1DAY_3C454.3.fits`

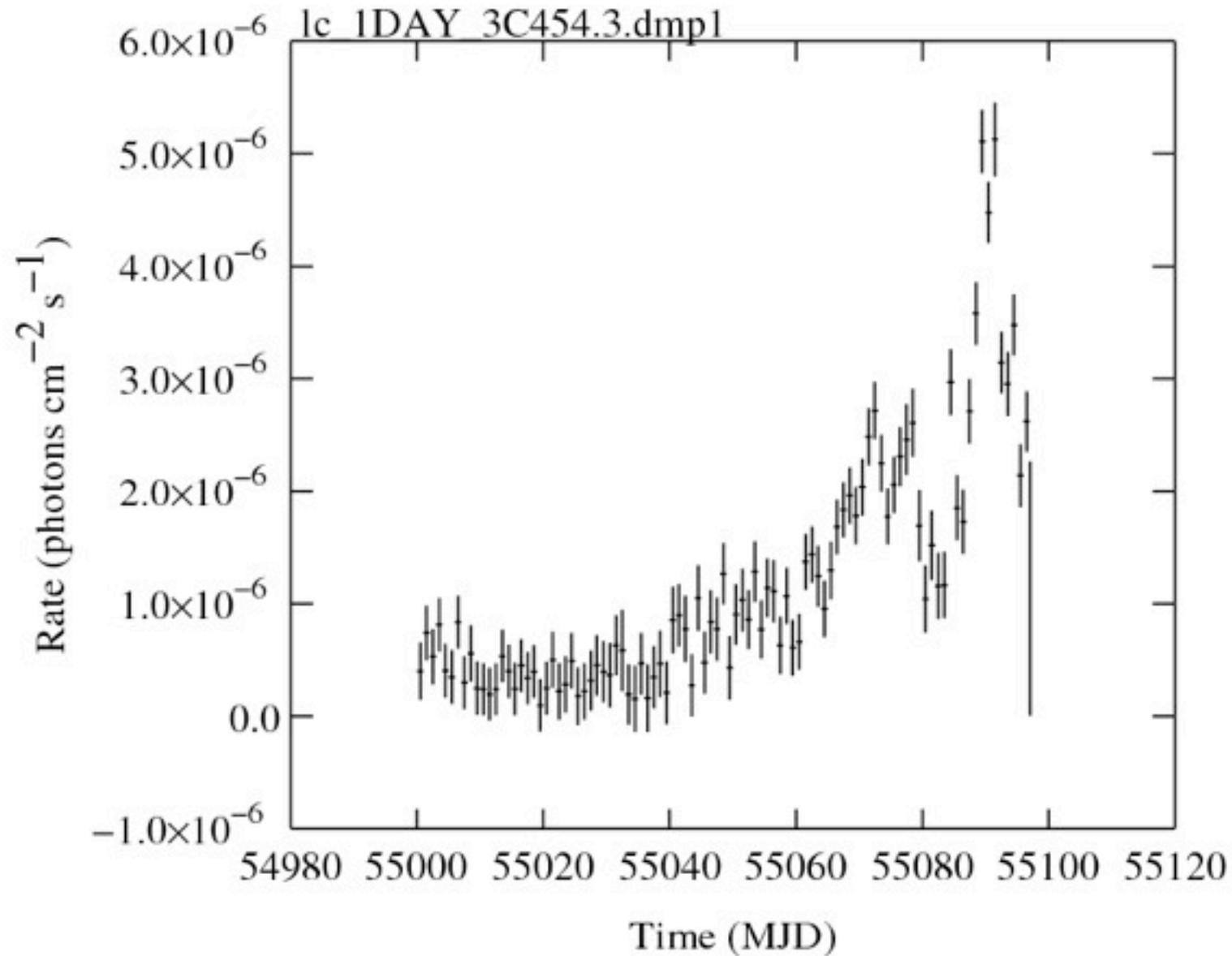
# The Output File

- The “final” file will contain Time (in MET), Bin width (s) number of counts in the bin, Error, Exposure.
- To convert to rates use e.g. fv or other software to divide counts by exposure. (Also useful to convert from MET to MJD.)
- Error bars in output file are  $\sqrt{\text{counts}}$ 
  - For (e.g.) few counts this may be incorrect.
  - To do things correctly is more complicated (see supplemental material).

# barycentering

- gtbary is advertised as doing barycenter corrections to photon files. However, it can also be used to barycenter light curves.
- gtbary must be done as the last step.
  - If you barycenter the input photon file, the exposure calculations will be wrong. (Don't do this!)
- Spacecraft file must cover longer (not same) time range than photon file.
  - Use gtselect to trim down time range of the photon file by a tiny amount (e.g. 60 seconds)

# Resulting Light Curve of 3C 454.3



# More Advanced Error Bar Treatment

- Dealing with error bars for small numbers of counts has been discussed in the astronomical literature by e.g.
  - Gehrels, 1986, ApJ, 303, 336
  - Kraft, Burrows, & Nousek, 1991, ApJ, 374, 344
- Useful review of concept of “coverage” by Heinrich in:
  - [www-cdf.fnal.gov/publications/cdf6438\\_coverage.pdf](http://www-cdf.fnal.gov/publications/cdf6438_coverage.pdf)

# Crude Approach to Low-Count Errors

- Instead of taking errors as  $N^{1/2}$ , where  $N$  is the observed number of counts, look at the ends of the error bars.
  - i.e. what underlying “population” count rate would be consistent with the “sample” count rate?
  - $\sigma = \pm 0.5 + \text{sqrt}(N + 0.25)$ 
    - e.g.  $0 \rightarrow 0, +1, -0$
    - $1 \rightarrow 1, +1.62, -0.62$
    - $2 \rightarrow 2, +2, -1$
- If needed, these errors can be “symmetrized”.

# Alternative: Exposure-Based Errors

- Calculate mean count rate.
- For each time bin, calculate the predicted number of counts for the exposure of that time bin.
- Take the square root of predicted number of counts.
- Divide by exposure to get rate error.
- This gives an error based only on the “quality” of each time bin.

# Scripting

- It is fairly easy to construct a script to do aperture photometry.
- On request, I can provide an example perl script (“bex”) that does
  - aperture photometry
  - rate based errors
  - exposure based errors
  - barycenter corrections
- But, “bex” also requires a small Fortran program to work.

# Part 2: Likelihood Photometry

- More details on likelihood analysis, and other useful presentations by LAT team members at a 2 week COSPAR workshop, (2010 Bangalore).
- [http://www.rri.res.in/fermi\\_cospar\\_2010/fermi-cospar-2010\\_files/lecture\\_files.html](http://www.rri.res.in/fermi_cospar_2010/fermi-cospar-2010_files/lecture_files.html)
- The presentations by B. Lott in particular are useful for an introduction to likelihood analysis of Fermi data.

# Likelihood Analysis Steps

- Create a source model
  - Select a spatial and temporal region:
    - `gtselect`, `gtmktime`
  - Calculate exposure
    - `gtlcube`, `gtexpmap`
  - Diffuse response
    - `gtdiffrsp`
  - Perform the fit
    - `gtlike`
  - Extract results (flux etc.) from `gtlike` output
- 

# Creating a Source Model

- This topic was covered in an earlier presentation.
- Depending on your objectives, the model files created with the user contributed script `make1FGLxml.py` can be very useful.
- For the generation of a light curve, the number of photons will typically be rather small.
  - The number of free parameters in the model cannot be too large. e.g. leave only flux and spectral index of source of interest free.
  - Time bins must be long enough to contain sufficient photons - restricts time resolution possible.

# Region/Temporal Selection

- Use `gtselect` to specify spatial and temporal data selection.
- For photometry this has two purposes.
  - Selecting the appropriate spatial region.
  - Repeated selection of time intervals so as to create a light curve.
- Repeated time selections cannot be done inside `gtlike` itself. Need to “wrap” `gtlike` inside a script and repeatedly call `gtselect`.

# like\_lc.pl

- This perl script is in the user contributed area.
- It is intended as an example, and might not meet your scientific needs...
- “like\_lc.pl -help” gives some information.
- You can either specify a model file, or else the script can generate one automatically using make1FGLxml.py
- To use make1FGLxml, the environment variable \$MY\_FERMI\_DIR must be set to a directory where both make1FGLxml.py and gll\_psc\_v02.fit (1FGL catalog) must be present.

# Inputs to like\_lc.pl

- A file containing a list of photon files (“plist.dat”)
  - e.g. from the workshop download area
    - LSI\_61\_303\_PH00.fits
- A file containing a list of source names and coordinates to analyze (“slist.dat”).
  - If the model file is to be auto-generated the source name must match the 1FGL name, without spaces.
  - e.g. for the binary “LSI +61 303”
    - 1FGLJ0240.5+6113, 40.1317, 61.2281
- Other parameters are prompted for on the command line...

# Running like\_lc.pl

```
$ like_lc.pl
like_lc.pl: V1.02
Auto-generate model files from 1FGL catalog? [y/n; default = y]:
(Using default: "Y")
auto model
Give minimum TS value for including fluxes in output [default = 2]: 3
Give source parameter file [default = slist.dat]:
(Using default: "slist.dat")
Give photon file name list [default = plist.dat]:
(Using default: "plist.dat")
Give spacecraft (FT2) file name [default = LSI_61_303__SC00.fits]:
(Using default: "LSI_61_303__SC00.fits")
Give aperture radius (degrees) [default = 10]: 9
Give Emin (MeV) [default = 100]:
(Using default: "100")
Give Emax (MeV) [default = 200000]:
(Using default: "200000")
Give Zenith limit (degrees) [default = 105]:
(Using default: "105")
Give EVENT_CLASS minimum (use 0 for simulated data) [default = 3]:
(Using default: "3")
Give Bore limit (degrees) [default = 180]:
(Using default: "180")
Give bin size (days) [default = 5]: 3
Getting sources
line = 1FGLJ0240.5+6113 40.1317, 61.2281
```

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Use < 10 degrees for workshop data

# Summary of like\_Ic Steps

```
gtselect chatter=0 zmax=180 emin=100 emax=200000 infile="@plist.dat" outfile='tmp_12426eventfile0.fits'  
ra=40.1317 dec=61.2281 rad=9 evclmin=3 evclmax=10 tmin=0 tmax=0
```

```
python tmp_12426pyfile.py (This is make1FGLxml version 03_rc. [...])
```

```
fkeypar "tmp_12426eventfile0.fits" TSTART (photon start time = 240000000.)
```

```
fkeypar "tmp_12426eventfile0.fits" TSTOP (photon stop time = 260000000.)
```

Stuff in the box is in a loop!

```
gtselect chatter=0 zmax=180 emin=100 emax=200000 infile="tmp_12426eventfile0.fits"  
outfile='tmp_12426eventfile1.fits' ra=40.1317 dec=61.2281 rad=9 evclmin=3 evclmax=10 tmin=240000000.  
tmax=240259200
```

```
gtmktime chatter=0 scfile="LSI_61_303_SC00.fits" filter="(DATA_QUAL==1) && (angsep(RA_ZENITH,DEC_ZENITH,  
40.1317,61.2281)+9<105) && (angsep(40.1317,61.2281,RA_SCZ,DEC_SCZ)<180)" roicut=n  
evfile="tmp_12426eventfile1.fits" outfile="tmp_12426eventfile2.fits"
```

```
gtlcube chatter=0 evfile=tmp_12426eventfile2.fits scfile=LSI_61_303_SC00.fits outfile=tmp_12426expcube.fits  
dcostheta=0.025 binsz=1  
Working on file LSI_61_303_SC00.fits
```

```
gtexpmap chatter=0 evfile=tmp_12426eventfile2.fits scfile=LSI_61_303_SC00.fits expcube=tmp_12426expcube.fits  
outfile=tmp_12426expmap.fits irfs=P6_V3_DIFFUSE srcrad=19 nlong=120 nlat=120 nenergies=20
```

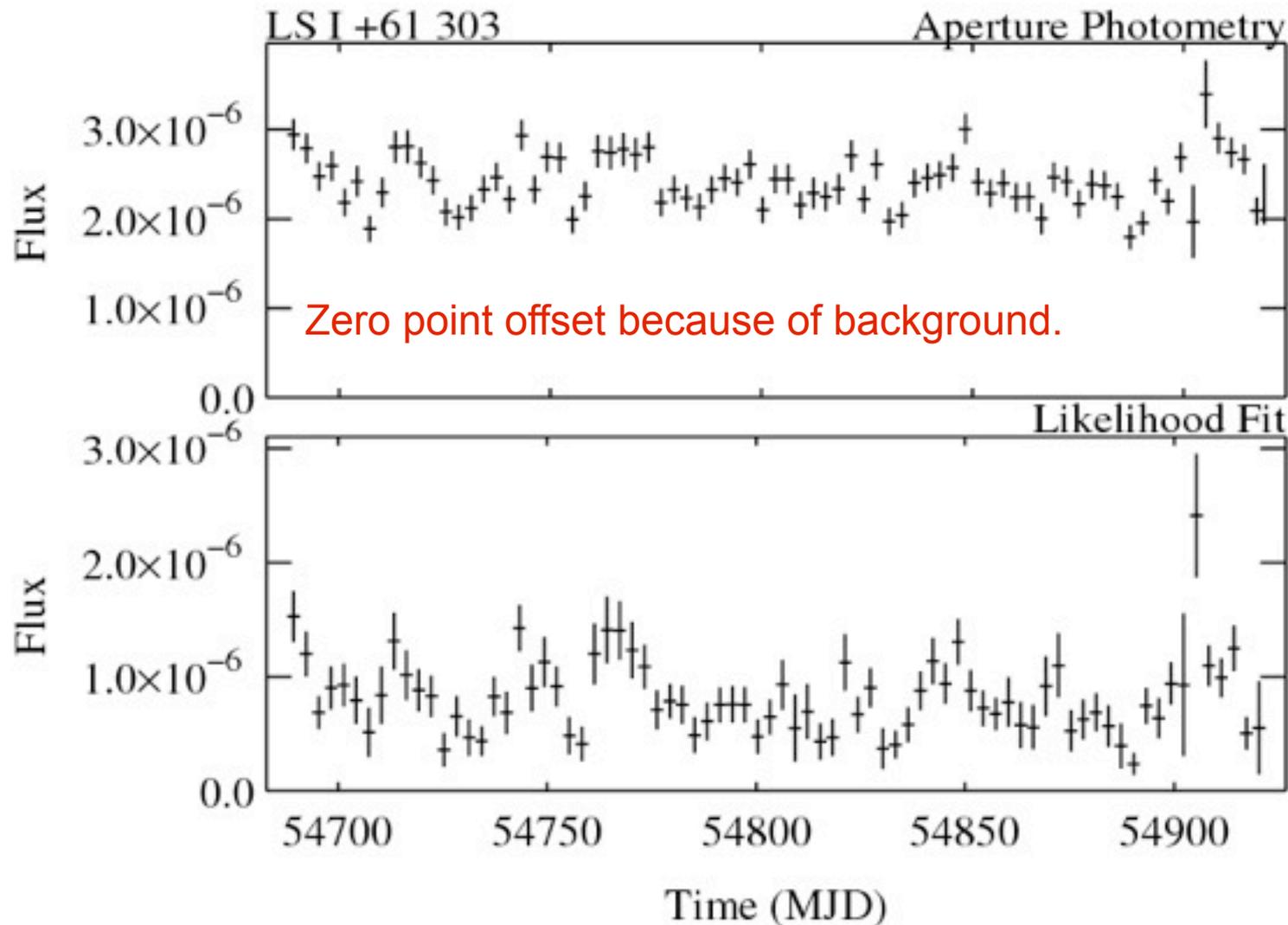
```
gtdiffrsp chatter=0 evfile='tmp_12426eventfile2.fits' scfile=LSI_61_303_SC00.fits srcmdl=edit_myLATxmlmodel.xml  
irfs=P6_V3_DIFFUSE
```

```
gtlike results=tmp_12426results.dat specfile=tmp_12426counts_spectra.fits chatter=0 irfs=P6_V3_DIFFUSE  
expcube=tmp_12426expcube.fits srcmdl=edit_myLATxmlmodel.xml statistic=UNBINNED optimizer=MINUIT  
evfile=tmp_12426eventfile2.fits scfile=LSI_61_303_SC00.fits expmap=tmp_12426expmap.fits cmap=none  
bexpmap=none
```

# Output of like\_lc.pl

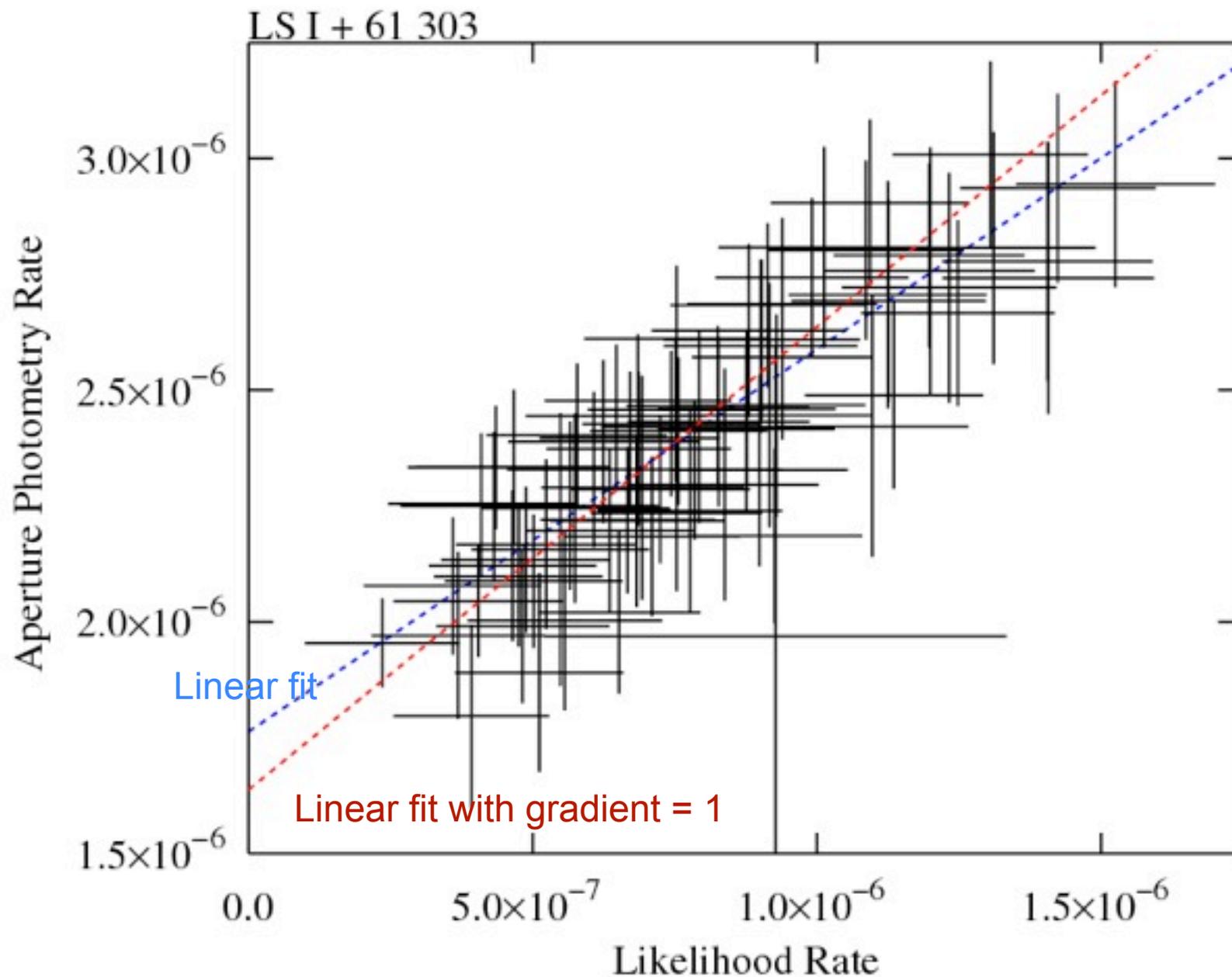
- While it's running, the script produces a lot of screen output.
- A number of temporary files are created in the directory where it is run, and then deleted.
- The output ASCII files have names of the form
  - `XXX_like_lc.dat` (XXX is the source name in)
- Columns are:
  - Time (MJD), flux (cts/cm<sup>2</sup>/s), flux error, bin half width (days), TS value, spectral index, index error
- Look out for bad points with low flux/small errors!
  - (Generally have low TS values.)

# Comparison of Two Methods (i)

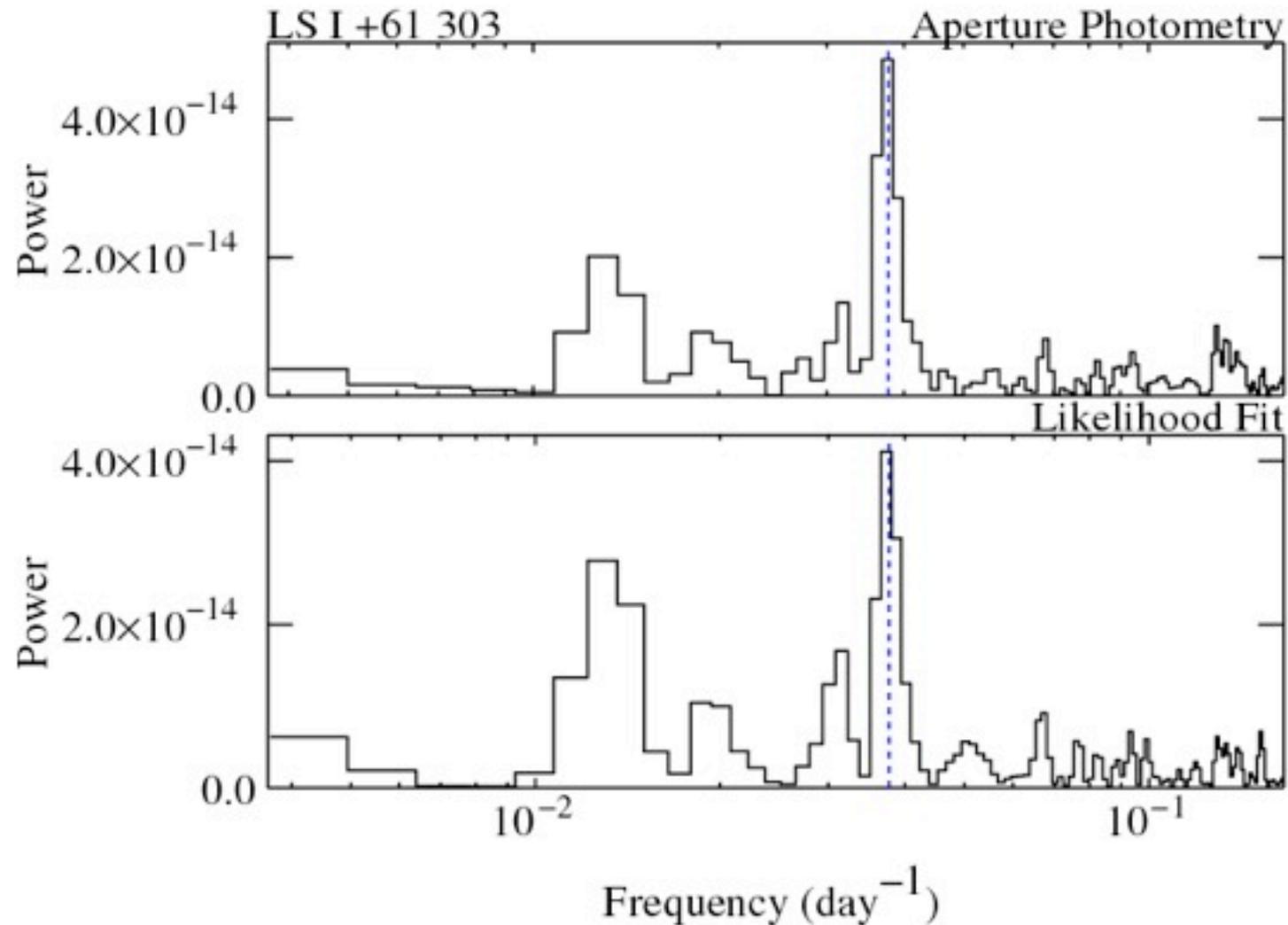


Binary system LS I +61 303 (1FGL J0240.5+6113) - varies on known 26.5 day period

# Photometry Comparison (ii)



# Photometry Comparison (iii)



Both light curves show known 26 day orbital period at similar significance.

# Summary

- LAT light curves can be obtained using either aperture photometry or likelihood analysis.
- Aperture photometry advantages:
  - Fast (~30 minutes for 2 yr lc., likelihood ~50x slower)
  - Model independent
  - Short time bins can be used (including bins with no photons)
- Likelihood analysis advantages:
  - Gives background-subtracted flux
  - No aperture size choice to maximize S/N needed
  - Potentially higher S/N (all photons used)